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Adolescence as a Unique Period of Vulnerability to Anabolic-Androgenic Steroid Exposure: A Narrative Review

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ABSTRACT

Introduction. The non-medical use of anabolic-androgenic steroids (AAS) is an increasingly important public health concern among adolescents, particularly males engaged in resistance training, appearance-oriented sports, and social media-driven muscularity culture. Adolescence represents a period of increased vulnerability because exposure to supraphysiological androgen concentrations occurs during ongoing endocrine, skeletal, reproductive, cardiovascular, and neuropsychiatric development. This narrative review synthesizes current evidence on the health consequences of adolescent AAS exposure, focusing on endocrine disruption, cardiovascular,

neuropsychiatric, and musculoskeletal complications, developmental vulnerability, and long-term health risks.

Brief description. Available evidence indicates that AAS exposure may suppress the hypothalamic-pituitary-gonadal axis, impair spermatogenesis, contribute to hypogonadism, and disrupt pubertal maturation. Reported cardiovascular complications include dyslipidaemia, hypertension, myocardial remodelling, cardiomyopathy, and increased cardiovascular risk. Neuropsychiatric effects include aggression, mood disturbances, dependence, withdrawal syndromes, and body image-related psychopathology. Additional concerns include hepatotoxicity, renal injury, gynecomastia, premature epiphyseal closure, and tendon rupture. However, direct evidence in adolescents remains limited, and many long-term risks are extrapolated from adult cohorts and developmental biology.

Conclusions. Adolescents should not be regarded simply as younger adult AAS users. Exposure during adolescence may disrupt critical biological and psychological development, potentially resulting in long-term health consequences. Prevention should emphasize early education, identification of body image-related risk factors, and multidisciplinary interventions targeting both health behaviours and psychosocial vulnerabilities.

Keywords: anabolic-androgenic steroids; adolescence; developmental vulnerability; muscle dysmorphia; endocrine disruption; cardiovascular risk

1. Introduction

Anabolic-androgenic steroids (AAS) are synthetic derivatives of testosterone used clinically in selected medical conditions but increasingly consumed for non-medical purposes related to muscular development, physical appearance, and athletic performance [2,17]. Although historically associated with elite sport and professional bodybuilding, AAS use has expanded into recreational strength training and adolescent populations [4,8,21,25].

Adolescence may represent a particularly vulnerable period for AAS exposure because supraphysiological androgen concentrations are introduced during ongoing skeletal growth, maturation of the hypothalamic-pituitary-gonadal axis, reproductive development, brain maturation, and psychosocial identity formation [9,10,17]. Consequently, the biological and psychological effects of AAS exposure during adolescence may differ from those observed in fully mature adults [9,10].

Although numerous reviews have examined the adverse effects of anabolic-androgenic steroids in adult athletes and bodybuilders [2,17,23], comparatively less attention has been devoted to adolescence as a distinct developmental period [10,21]. Moreover, many health consequences associated with AAS use have been described primarily in adult populations, creating uncertainty regarding their implications for individuals exposed during ongoing biological and psychological maturation [10,17,18]. A developmental perspective may therefore provide additional insight into the potential risks associated with adolescent AAS exposure.

The purpose of this narrative review was to synthesize current evidence regarding the health consequences of anabolic-androgenic steroid exposure during adolescence, with particular emphasis on developmental vulnerability, endocrine disruption, cardiovascular complications, neuropsychiatric effects, musculoskeletal consequences, reproductive health, and long-term medical risks.

A narrative literature search was conducted using PubMed, Scopus, and Google Scholar databases. Additional relevant publications were identified through reference screening. Priority was given to systematic reviews, meta-analyses, observational studies, narrative reviews, and clinically relevant publications addressing AAS use and its health consequences. Selected articles from Journal of Education, Health and Sport and Quality in Sport were additionally considered when they provided relevant complementary evidence not sufficiently addressed in the mainstream medical literature. Due to substantial heterogeneity in study design, study populations, exposure assessment, and outcome measures, a narrative rather than systematic review methodology was considered more appropriate.

2. Epidemiology and Drivers of AAS Use Among Adolescents

The non-medical use of anabolic-androgenic steroids (AAS) is no longer limited to elite athletes or competitive bodybuilders. Contemporary evidence indicates that AAS use also occurs among adolescents and young adults in contexts related to muscularity, body image, recreational resistance training, and broader patterns of risk behaviour [4,8,21,25,27]. Reported prevalence varies substantially depending on country, sex, study methodology, and whether investigations assess lifetime use, recent use, or use specifically intended to increase muscularity [4,8,24,25].

Although AAS use has traditionally been associated with competitive sport, appearance enhancement and muscularity have become increasingly important motivations among

adolescents. Schneider et al. demonstrated significant associations between adolescent AAS use and other substance-use behaviours, suggesting that steroid use frequently occurs within a broader profile of health-risk behaviours rather than as an isolated performance-enhancement strategy [4,8,9,25].

2.1. Body Image Concerns and Muscularity Ideals

Body image concerns have emerged as an important driver of adolescent AAS use. While earlier research focused primarily on thinness-oriented ideals among females, recent studies highlight increasing muscularity-oriented concerns among boys and young men [14,21]. Cultural ideals linking muscular physiques with attractiveness, confidence, masculinity, and social status may contribute to body dissatisfaction and increase interest in pharmacological physique enhancement [14,15].

Adolescents experiencing muscularity-related dissatisfaction appear more likely to consider AAS use, particularly when accompanied by compulsive exercise, perfectionistic traits, or concerns regarding social evaluation [14,21,26]. Together, these findings suggest that body image pathology represents an important pathway toward AAS initiation.

2.2. Social Media and the Modern Muscularity Culture

Social media has fundamentally changed the environment in which adolescents develop body image. Continuous exposure to highly curated physique-oriented content promotes exceptionally muscular and lean bodies as desirable and attainable while facilitating repeated appearance comparisons with peers, influencers, and fitness communities [15].

Such exposure has been associated with greater body dissatisfaction, unrealistic expectations regarding physical development, and stronger intentions to use AAS among boys and young men [14,15]. Rather than acting as a direct cause of steroid use, social media appears to amplify pre-existing vulnerabilities — including low self-esteem, perfectionism, and social anxiety — while online communities may normalize pharmacological enhancement and downplay potential health risks [15,21].

2.3. Muscle Dysmorphia and Psychological Vulnerability

Muscle dysmorphia is increasingly recognized as an important psychological factor associated with adolescent AAS use. The disorder is characterized by a persistent belief that one's body is insufficiently muscular despite often possessing above-average muscularity and is commonly accompanied by compulsive exercise, restrictive dietary practices, body checking, and avoidance behaviours [21].

Symptoms of muscle dysmorphia have been associated with intentions to use AAS, actual steroid use, and dependence-related features, suggesting that steroid use may function as an attempt to alleviate body image-related distress rather than solely improve athletic performance [21,26].

2.4. Why Adolescents Are Particularly Vulnerable

Adolescence is characterized by ongoing neurobiological and psychosocial development, including identity formation, heightened sensitivity to peer influence, increased reward responsiveness, and an evolving self-concept [10]. Compared with adults, adolescents may place greater value on immediate social rewards while underestimating long-term health consequences, increasing susceptibility to rapid appearance-enhancing strategies.

Current evidence supports a developmental model in which adolescent AAS use results from interactions among biological vulnerability, psychological factors, social influences, and environmental exposure [8,14,21]. Rather than representing a purely rational performance-enhancement decision, steroid use should be understood as a multifactorial phenomenon shaped by developmental processes unique to adolescence. This framework provides an important context for interpreting the biological consequences discussed in subsequent sections, particularly given the ongoing maturation of endocrine and reproductive systems [9,10,12,17].

3. Endocrine Disruption During a Critical Developmental Period

Among all organ systems affected by anabolic-androgenic steroids (AAS), the endocrine system may be particularly vulnerable during adolescence because exposure occurs while hormonal regulatory pathways are still maturing. Unlike adults, adolescents undergo active development of the hypothalamic-pituitary-gonadal (HPG) axis, pubertal progression, reproductive maturation, and longitudinal skeletal growth. Consequently, endocrine

disturbances induced by supraphysiological androgen exposure may have implications extending beyond the transient hormonal suppression commonly described in adult users [6,9,10,17,18].

Direct prospective evidence in adolescent AAS users remains limited; therefore, the following discussion integrates adolescent studies with evidence from adult cohorts and established principles of endocrine physiology and developmental biology [9,10,12,17].

3.1. Suppression of the Hypothalamic-Pituitary-Gonadal Axis

The HPG axis plays a central role in regulating reproductive and endocrine function. Physiologically, gonadotropin-releasing hormone (GnRH) secreted by the hypothalamus stimulates pituitary release of luteinizing hormone (LH) and follicle-stimulating hormone (FSH), which subsequently regulate testicular testosterone production and spermatogenesis. Administration of exogenous AAS disrupts this feedback system by suppressing endogenous GnRH, LH, and FSH secretion through negative feedback mechanisms [12,17,18,19].

Evidence from both clinical and observational studies demonstrates that AAS use is associated with profound suppression of gonadotropin secretion and endogenous testosterone production [12,17,18]. While recovery of HPG-axis function may occur following discontinuation, the duration and completeness of recovery appear highly variable and may depend on age, duration of exposure, cumulative dose, and individual susceptibility [12,17,19].

The consequences of HPG-axis suppression may be particularly relevant in adolescents because exposure occurs during a period when endocrine regulatory pathways are still undergoing maturation. Unlike adults who have completed pubertal development, adolescents may experience interference with normal hormonal programming, raising concerns regarding long-term reproductive and endocrine outcomes [10,17,18].

3.2. Interference with Pubertal Development

Puberty represents a complex biological process involving coordinated activation of endocrine pathways responsible for sexual maturation, body composition changes, reproductive development, and skeletal growth. Exposure to supraphysiological androgen concentrations may disrupt these physiological processes by altering normal hormonal signalling patterns [9,10].

Although androgens are essential for male pubertal development, excessive exogenous androgen exposure does not simply accelerate normal maturation. Instead, supraphysiological concentrations may impair the finely regulated hormonal balance required for physiological development [9,10,17]. Clinical reports and experimental evidence suggest that AAS exposure during adolescence may contribute to abnormalities in pubertal progression, endocrine dysfunction, and disturbances in normal reproductive maturation [9,10].

Importantly, the developing endocrine system may demonstrate greater sensitivity to hormonal perturbation than the mature adult system. Consequently, endocrine consequences observed during adolescence should not be interpreted as merely younger versions of those reported in adult users [10,17].

3.3. Fertility and Testicular Function

Suppression of gonadotropin secretion represents one of the principal mechanisms through which AAS impair fertility. Reduced LH secretion decreases intratesticular testosterone production, whereas reduced FSH levels impair Sertoli cell function and spermatogenesis [12,18,19,28].

Numerous studies have documented reduced sperm concentration, oligospermia, azoospermia, testicular atrophy, and impaired fertility among AAS users [12,18,19,28]. Desai et al. emphasized that suppression of spermatogenesis may persist for months following cessation of androgen exposure, although recovery is possible in many individuals [12]. Similarly, Whitaker et al. highlighted growing evidence linking anabolic steroid misuse with clinically significant impairment of male fertility [28].

However, direct evidence regarding long-term fertility outcomes among adolescents remains limited. Much of the available literature derives from adult users, and extrapolation to adolescents should therefore be interpreted cautiously [12,18,28]. Nevertheless, exposure during critical stages of gonadal maturation may plausibly influence both immediate reproductive function and future fertility potential.

3.4. Gynecomastia and Hormonal Imbalance

Gynecomastia represents one of the most recognizable endocrine complications associated with AAS use. Although anabolic steroids are androgenic compounds, many can undergo

aromatization to estradiol, resulting in elevated estrogenic activity and disruption of the physiological androgen-to-estrogen balance [9,17,18].

Increased estrogenic stimulation of breast tissue may lead to glandular proliferation and clinically apparent gynecomastia [9,18]. The risk appears particularly relevant among users exposed to high doses, prolonged treatment periods, or compounds with significant aromatization potential [17].

From a developmental perspective, gynecomastia may be especially distressing during adolescence because body image, social acceptance, and self-esteem are undergoing active formation. Therefore, the consequences of AAS-induced hormonal imbalance may extend beyond physical manifestations and contribute to psychosocial distress in affected individuals [21,26].

3.5. Premature Epiphyseal Closure and Growth Disturbance

One of the most distinctive risks associated with adolescent AAS exposure is premature closure of the epiphyseal growth plates. Unlike adults, adolescents retain open physes that permit longitudinal bone growth. Exposure to excessive androgen concentrations may accelerate skeletal maturation and promote premature epiphyseal fusion, potentially limiting final adult height [9,10]. This complication is particularly important because it represents one of the few adverse effects largely unique to individuals who have not yet completed skeletal development. While many endocrine disturbances associated with AAS use may improve following cessation, premature physeal closure may result in irreversible consequences [9]. Because epiphyseal fusion is a normal endpoint of puberty, premature activation of this process may shorten the remaining growth period and permanently reduce growth potential [9,10].

Current evidence directly documenting this outcome in adolescent AAS users remains limited. Nevertheless, the established physiology of skeletal maturation and available developmental evidence support continued concern regarding this potential complication [9,10].

While endocrine disruption represents the most direct consequence of supraphysiological androgen exposure during adolescence, the effects of AAS are not limited to hormonal regulation. Emerging evidence suggests that cardiovascular alterations — including dyslipidaemia, hypertension, myocardial remodelling, and cardiomyopathy — may begin early

in the course of AAS use and contribute to the accumulation of long-term cardiovascular risk decades before clinical disease becomes apparent [3,5,13,20,29].

4. Cardiovascular Adaptations and Long-Term Risk Accumulation

Cardiovascular complications are among the most serious adverse effects of anabolic-androgenic steroid (AAS) exposure. Although overt cardiovascular disease usually develops later in life, supraphysiological androgen exposure may initiate structural, functional, and metabolic changes long before clinical manifestations become apparent. When exposure occurs during adolescence, these processes may begin earlier and contribute to long-term cardiovascular risk. However, because most available evidence derives from adult or mixed-age cohorts, conclusions regarding adolescent users remain based primarily on biological plausibility rather than direct longitudinal evidence [3,5,7,13,20,29].

4.1. Dyslipidaemia and Early Atherogenic Changes

Among the most consistently reported cardiovascular consequences of AAS exposure is adverse alteration of lipid metabolism. Multiple studies have documented substantial reductions in high-density lipoprotein cholesterol (HDL-C) accompanied by elevations in low-density lipoprotein cholesterol (LDL-C), resulting in a more atherogenic lipid profile [3,7,20].

The magnitude of these alterations appears to depend on the specific compound, route of administration, dosage, and duration of exposure. Oral 17α-alkylated steroids appear particularly detrimental, although adverse lipid changes have also been reported among users of injectable preparations [20].

These findings are especially relevant because atherosclerosis is increasingly recognized as a lifelong process that begins long before clinical cardiovascular disease becomes evident. Exposure to profoundly unfavourable lipid profiles during adolescence may therefore contribute to cumulative vascular injury and accelerated atherogenesis over time [3,20,29].

Although lipid abnormalities frequently improve after discontinuation of AAS use, the long-term implications of repeated exposure-and-recovery cycles remain incompletely understood, particularly among individuals initiating use during adolescence [5,20].

4.2. Hypertension and Vascular Dysfunction

Elevated blood pressure has been repeatedly reported among AAS users and may represent another mechanism contributing to cardiovascular risk accumulation [3,13,20].

Several physiological mechanisms have been proposed, including sodium and water retention, increased sympathetic nervous system activity, endothelial dysfunction, altered vascular reactivity, and reduced arterial compliance [13,20]. Over time, persistent elevations in blood pressure may increase myocardial workload and contribute to structural cardiac remodelling [3,13].

Beyond hypertension itself, growing evidence suggests that AAS exposure may impair endothelial function. Endothelial dysfunction is considered an early step in the pathogenesis of atherosclerosis and may contribute to adverse cardiovascular outcomes even in relatively young individuals [20,29].

Although direct adolescent-specific evidence remains limited, these findings raise concern because vascular injury initiated during adolescence may remain clinically silent for many years before manifesting as overt cardiovascular disease [13,20].

4.3. Cardiac Remodelling and Left Ventricular Hypertrophy

Cardiac remodelling represents one of the most extensively investigated cardiovascular consequences of chronic AAS exposure. Imaging studies have demonstrated increases in left ventricular wall thickness, alterations in chamber geometry, and structural myocardial changes among long-term users [3,13,20].

Importantly, steroid-associated remodelling appears to differ from the physiological adaptations observed in the so-called athlete's heart. While athletic training typically produces adaptive and largely reversible structural changes, AAS-associated remodelling may be accompanied by impaired ventricular relaxation, myocardial fibrosis, and reduced cardiac efficiency [3,13].

Baggish et al. demonstrated that chronic AAS users may exhibit both structural and functional cardiac abnormalities, including impaired left ventricular systolic performance despite

preserved exercise capacity [3]. These observations suggest that clinically silent myocardial injury may occur before overt symptoms become apparent.

Because adolescence is itself associated with physiological cardiovascular adaptation to growth and exercise, the interaction between developmental remodelling and supraphysiological androgen exposure remains insufficiently understood and warrants further investigation [7,13].

4.4. Cardiomyopathy and Heart Failure Risk

Accumulating evidence indicates that prolonged AAS exposure may contribute to the development of cardiomyopathy. Reported abnormalities include impaired ventricular function, myocardial fibrosis, reduced contractility, and progressive deterioration of cardiac performance [5,13].

Although much of the available literature involves adult users, severe myocardial injury has been reported even in relatively young individuals exposed to high doses of AAS [13,20]. Experimental studies further support direct toxic effects of supraphysiological androgen concentrations on cardiomyocytes, potentially contributing to apoptosis, fibrosis, and adverse myocardial remodelling [13].

One particularly concerning aspect is that cardiomyopathy may remain clinically silent for prolonged periods. Consequently, users may continue exposure despite ongoing structural cardiac damage [13].

Current evidence suggests that some cardiac abnormalities may improve after cessation of AAS use, although complete reversibility has not been consistently demonstrated. Therefore, the long-term consequences of adolescent exposure remain uncertain but biologically concerning [3,13,29].

4.5. Thrombotic Risk and Major Cardiovascular Events

In addition to chronic cardiovascular alterations, AAS exposure has been associated with acute cardiovascular events, including myocardial infarction, ischemic stroke, pulmonary embolism, and sudden cardiac death [3,20,29].

Several mechanisms may contribute to this increased risk, including endothelial dysfunction, accelerated atherosclerosis, enhanced platelet aggregation, polycythaemia, dyslipidaemia, and alterations in coagulation pathways [20,29].

Although such events remain uncommon among adolescents, their occurrence in young individuals without traditional cardiovascular risk factors is clinically significant. Furthermore, initiation of AAS use during adolescence may extend cumulative exposure to prothrombotic and proatherogenic influences across many years of life [20,29].

Recent population-based evidence has strengthened concerns regarding increased cardiovascular morbidity and mortality among AAS users [29]. However, interpretation should remain cautious because many users also engage in behaviours that independently influence cardiovascular risk, including stimulant use, extreme dietary practices, and intensive training regimens [29].

Taken together, the available evidence suggests that AAS exposure may create a cardiovascular environment characterized by both chronic structural remodelling and increased susceptibility to acute vascular events [3,13,20,29].

While cardiovascular complications represent some of the most serious long-term medical consequences of AAS exposure, adolescence is also characterized by ongoing maturation of cortical and limbic brain networks involved in emotional regulation, reward processing, impulse control, and decision-making. Consequently, neuropsychiatric consequences of AAS exposure may differ substantially from those observed in mature adults and warrant separate consideration [10,17,23,26].

5. Neuropsychiatric Effects on the Developing Brain

The neuropsychiatric consequences of anabolic-androgenic steroid (AAS) exposure represent one of the most complex and clinically important aspects of steroid misuse. While cardiovascular and endocrine complications often receive greater attention, growing evidence suggests that supraphysiological androgen exposure may influence emotional regulation, behavior, cognition, and mental health [10,17,23]. These effects may be particularly relevant during adolescence, a developmental period characterized by ongoing maturation of neural circuits involved in impulse control, reward processing, emotional regulation, and executive functioning [10].

Although most neuropsychiatric evidence derives from adult or mixed-age populations, adolescence represents a period of active brain maturation, providing a biologically plausible basis for increased vulnerability to supraphysiological androgen exposure [10,17,23,25].

5.1. Brain Development During Adolescence

Adolescence is characterized by extensive neurodevelopmental changes involving cortical maturation, synaptic pruning, myelination, and reorganization of neural networks responsible for higher cognitive functions [10]. The prefrontal cortex, which plays a central role in planning, decision-making, impulse control, and risk assessment, continues to mature well into early adulthood. In contrast, limbic structures involved in emotional processing and reward sensitivity often mature earlier, creating a temporary imbalance between emotional reactivity and executive control [10].

This developmental asymmetry has important implications for substance use and risk-taking behaviours. Adolescents generally demonstrate greater sensitivity to rewarding stimuli and may therefore be more vulnerable to behaviours associated with immediate gratification. Exposure to AAS occurs within this neurodevelopmental context and may interact with processes already influencing sensation-seeking, social comparison, and experimentation [10].

Experimental evidence suggests that androgen receptors are widely distributed throughout the central nervous system, including regions involved in emotion, motivation, reward processing, and social behaviour. Consequently, supraphysiological androgen exposure may influence neural circuits extending far beyond those traditionally associated with reproductive function [10,23].

5.2. Aggression and Behavioural Dysregulation

Perhaps the most widely recognized neuropsychiatric consequence of AAS exposure is increased aggression. Popular media frequently describe this phenomenon as “roid rage,” although the scientific literature suggests that the relationship between AAS use and aggressive behaviour is considerably more nuanced [17,23].

Current evidence indicates that AAS exposure may be associated with increased irritability, hostility, impulsivity, and aggressive behaviour in susceptible individuals [17,23]. However, not all users experience these effects, suggesting that genetic predisposition, personality traits,

environmental influences, psychiatric vulnerability, and concurrent substance use likely influence individual risk [17].

Piacentino et al. reported associations between AAS use and a range of psychopathological manifestations, including aggression and behavioural disturbances [23]. Similarly, Kanayama et al. noted that psychiatric complications may occur particularly among individuals exposed to high doses and prolonged periods of use [17].

From a developmental perspective, these observations may be especially important because emotional regulation systems remain under active maturation during adolescence. Increased impulsivity or aggression during this stage may influence interpersonal relationships, academic functioning, social development, and risk-taking behaviours [10].

Importantly, current evidence does not support the simplistic conclusion that AAS invariably cause aggression. Rather, supraphysiological androgen exposure appears to interact with pre-existing biological and psychosocial vulnerabilities, potentially amplifying aggressive tendencies in susceptible individuals [17,23].

5.3. Mood Disturbances and Emotional Instability

Beyond aggression, AAS exposure has been associated with a broad spectrum of mood-related disturbances. Reported manifestations include irritability, emotional lability, anxiety symptoms, depressive episodes, hypomanic states, and difficulties with emotional regulation [17,23].

Several mechanisms have been proposed to explain these associations. Experimental studies suggest that supraphysiological androgen exposure may influence serotonergic, dopaminergic, and GABAergic neurotransmission, thereby affecting neural pathways involved in mood regulation and reward processing [10]. However, the precise neurobiological mechanisms remain incompletely understood.

Clinical observations indicate that mood disturbances may occur both during active AAS exposure and following discontinuation [17]. During exposure, some users report increased confidence, elevated mood, and subjective improvements in well-being. In contrast, withdrawal periods may be associated with fatigue, dysphoria, depressive symptoms, reduced motivation, and emotional instability [17,18].

These fluctuations may be particularly disruptive during adolescence because emotional stability, self-concept, and identity formation are still developing. Consequently, repeated cycles of AAS exposure and withdrawal may interfere with normal psychological maturation, although direct evidence for long-term developmental effects remains limited [10,17].

5.4. Dependence and Withdrawal Syndromes

Although AAS are not traditionally classified alongside substances such as opioids, stimulants, or alcohol, accumulating evidence supports the existence of anabolic-androgenic steroid dependence as a clinically relevant condition [17,18,24].

Kanayama et al. proposed that AAS dependence should be recognized as a distinct disorder characterized by continued use despite adverse consequences, unsuccessful attempts to discontinue use, persistent preoccupation with steroid acquisition, and ongoing use despite awareness of harm [18]. Epidemiological studies further suggest that a meaningful proportion of long-term users may develop dependence-like patterns of behaviour [24].

Several mechanisms may contribute to this process. Users often experience substantial improvements in muscularity, strength, body composition, and perceived attractiveness during exposure. These changes may reinforce continued use through both biological reward pathways and psychosocial reinforcement [18,21,26].

Withdrawal symptoms may further perpetuate the cycle. Reported manifestations include depressed mood, insomnia, fatigue, decreased libido, anxiety, and diminished self-esteem [17,18]. In some individuals, withdrawal-associated depression may become severe and require psychiatric intervention [17].

Adolescents may be particularly vulnerable because self-image, peer acceptance, and identity formation play especially prominent roles during this developmental stage. Consequently, discontinuation may be perceived not merely as loss of a drug effect, but as loss of an important component of personal identity and social status [21,26].

5.5. Muscle Dysmorphia and Body Image Pathology

Body image pathology may also interact with neuropsychiatric vulnerability and dependence. Symptoms of muscle dysmorphia have been associated with intentions to use AAS, actual

steroid use, and dependence-related behaviours, suggesting that steroid use may function as an attempt to alleviate appearance-related distress rather than simply enhance performance [14,21,26]. This distinction is particularly relevant in adolescents, among whom appearance-related motivations may be as important as, or more important than, competitive athletic goals [14,15,21].

5.6. Long-Term Neuropsychiatric Implications

Despite growing concern regarding the neuropsychiatric effects of AAS exposure, important uncertainties remain. Much of the available evidence derives from adult users, retrospective studies, or populations with concurrent psychiatric disorders and substance use, limiting causal inference [17,23].

Nevertheless, current evidence supports the hypothesis that adolescence may represent a particularly sensitive developmental period during which supraphysiological androgen exposure interacts with ongoing brain maturation. Potential consequences include disturbances in emotional regulation, increased impulsivity, mood instability, body image pathology, and dependence-related behaviours [10,17].

At present, the strongest conclusion supported by the literature is not that AAS exposure definitively alters adolescent neurodevelopment, but rather that exposure occurs during a period of heightened neurobiological vulnerability. Further prospective research specifically involving adolescent populations is required to determine the magnitude and persistence of these effects [10].

While neuropsychiatric consequences highlight the vulnerability of the developing brain, adolescence is also characterized by ongoing skeletal growth, musculoskeletal maturation, and adaptation of connective tissues to increasing mechanical demands. Consequently, exposure to supraphysiological androgen concentrations may influence not only muscle development but also tendons, growth plates, and long-term orthopaedic health, creating another domain in which adolescents differ fundamentally from adult AAS users [9,16,19].

6. Musculoskeletal Development Under Supraphysiological Androgen Exposure

The musculoskeletal system represents another domain in which adolescents differ fundamentally from adult anabolic-androgenic steroid (AAS) users. During adolescence,

skeletal growth, physeal maturation, muscle development, tendon adaptation, and bone remodelling remain active processes. Consequently, exposure to supraphysiological androgen concentrations occurs during ongoing musculoskeletal development, potentially producing effects that differ from those observed in mature adults [9,10,16]. Although several musculoskeletal concerns are biologically plausible, direct prospective evidence in adolescent users remains limited, and much of the available knowledge is derived from developmental biology, experimental studies, orthopaedic physiology, and adult AAS cohorts [9,10,16].

AAS markedly accelerate gains in muscle mass and strength, but adaptation of the musculoskeletal system requires coordinated remodelling of muscles, tendons, ligaments, bone, and growth plate cartilage. As a result, rapid pharmacologically induced increases in muscle strength may outpace connective tissue adaptation, potentially increasing susceptibility to musculoskeletal injury [16,19].

6.1. Muscle Growth and Tendon Adaptation Mismatch

The anabolic effects of AAS on skeletal muscle are well established. Supraphysiological androgen exposure stimulates protein synthesis, promotes muscle fibre hypertrophy, enhances recovery capacity, and contributes to substantial increases in lean body mass and strength [2].

However, muscle tissue is not the only structure exposed to increasing mechanical demands. Tendons must simultaneously adapt to transmit the greater forces generated by enlarged and strengthened muscles. Available evidence suggests that tendon adaptation may occur more slowly than muscular adaptation, potentially creating a mismatch between force production and connective tissue resilience [16].

Experimental and clinical studies have demonstrated that AAS may influence collagen metabolism, tendon ultrastructure, and biomechanical properties. Some investigators have proposed that while muscles become stronger, tendons may become relatively more vulnerable to injury under conditions of extreme loading [16,19].

This phenomenon may be particularly relevant during adolescence because musculoskeletal tissues are simultaneously adapting to physiological growth and increasing mechanical demands associated with physical activity. Consequently, pharmacologically accelerated muscular development may place additional stress on structures that remain under active maturation [10,16].

6.2. Tendon Ruptures and Connective Tissue Injury

Among the most widely recognized orthopaedic complications associated with AAS use are tendon ruptures. Although relatively uncommon in the general population, tendon ruptures have been reported with increased frequency among long-term steroid users, particularly in strength-training populations [19].

Kanayama et al. reported a significantly higher prevalence of tendon ruptures among AAS users compared with non-users, with injuries commonly involving the pectoralis major, distal biceps tendon, triceps tendon, quadriceps tendon, and Achilles tendon [19]. Such injuries often occur during high-force activities and may require surgical treatment.

Several mechanisms have been proposed. First, accelerated increases in muscle strength may expose tendons to loads exceeding their adaptive capacity. Second, alterations in collagen organization and extracellular matrix composition may negatively influence tendon mechanical properties [16,19].

Direct evidence regarding tendon rupture risk in adolescent AAS users remains limited. However, because adolescence is characterized by ongoing musculoskeletal maturation, these observations raise concerns regarding the potential interaction between growth-related adaptation and pharmacologically enhanced strength gains [10,16].

6.3. Premature Epiphyseal Closure and Skeletal Maturation

One of the most distinctive musculoskeletal concerns associated with adolescent AAS exposure is premature closure of the epiphyseal growth plates. Unlike adults, adolescents retain open physes that permit continued longitudinal bone growth and contribute to final adult stature [9].

As discussed in the endocrine section, excessive androgen exposure may accelerate skeletal maturation and promote premature physeal fusion. Although androgens play an essential role in normal pubertal growth, supraphysiological concentrations may disrupt the physiological timing of skeletal maturation [9,10].

This complication deserves particular emphasis because it represents one of the few adverse effects largely unique to individuals who have not yet completed skeletal development. While many complications associated with AAS exposure may partially improve following

discontinuation, premature epiphyseal closure may result in permanent loss of growth potential [9].

Current evidence directly documenting this outcome in adolescent AAS users remains limited. Nevertheless, the established physiology of skeletal maturation, combined with available developmental evidence, supports continued concern regarding this potential complication [9,10].

6.4. Bone Health and Skeletal Development

The relationship between AAS exposure and bone health is complex. Physiological androgen concentrations play an important role in bone mineralization, skeletal growth, and pubertal development. However, the effects of chronic supraphysiological exposure during adolescence remain incompletely understood [9,16].

Some adult studies have reported increases in bone mineral density among AAS users. However, such findings should not be interpreted as evidence that adolescent exposure is beneficial. Bone development during adolescence involves tightly coordinated interactions among sex steroids, growth hormone, insulin-like growth factor-1, mechanical loading, and nutritional factors [9].

Consequently, interference with these developmental processes may have effects that differ substantially from those observed in mature adults. Moreover, bone density alone does not fully reflect skeletal health, as bone architecture, quality, and developmental timing may also influence long-term orthopaedic outcomes [16].

6.5. Long-Term Orthopaedic Implications

Although cardiovascular and endocrine complications often receive greater attention, musculoskeletal consequences may substantially influence long-term quality of life. Tendon ruptures, growth disturbances, chronic pain, recurrent injury, and persistent functional limitations may affect athletic participation, occupational performance, and overall physical function [16,19].

Importantly, many adolescents initiate AAS use to improve physical performance or appearance. Ironically, some resulting complications may directly impair long-term

musculoskeletal health and athletic capacity. This paradox highlights the importance of considering adolescent AAS exposure within a developmental framework rather than solely through the lens of short-term performance enhancement [9,16].

Taken together, the available evidence suggests that the adolescent musculoskeletal system should be regarded as another domain of developmental vulnerability. Although direct adolescent-specific evidence remains limited for several outcomes, exposure to supraphysiological androgen concentrations during ongoing growth may plausibly influence muscles, tendons, bones, and growth plates in ways that differ substantially from those observed in fully mature adults [9,10,16].

While musculoskeletal complications illustrate how AAS exposure may interfere with physical development, the adverse effects of these substances are not limited to the endocrine, cardiovascular, neuropsychiatric, and orthopaedic systems. Increasing evidence suggests that anabolic steroids may also affect hepatic and renal function, contributing to both acute and chronic organ injury. Although these complications are not unique to adolescence, their occurrence during a period of ongoing physiological development may further increase long-term health risks [1,11,22].

7. Hepatic and Renal Consequences

Although cardiovascular, endocrine, and neuropsychiatric complications receive the greatest clinical attention, hepatic and renal injury represents an important component of the systemic toxicity associated with anabolic-androgenic steroid (AAS) exposure. As the primary organs responsible for metabolism and excretion, the liver and kidneys are particularly susceptible to chronic supraphysiological androgen exposure [1,11,22].

Although hepatic and renal toxicity is not unique to adolescence, early exposure may increase the cumulative burden of organ injury across the lifespan. Most available evidence derives from adult users, case reports, observational studies, and mixed-age cohorts; therefore, adolescent-specific risks remain incompletely defined [1,11,22].

Many adolescents also underestimate the multisystem toxicity of AAS, perceiving these substances primarily as affecting reproductive function. This misconception may delay recognition of complications and contribute to continued use despite emerging symptoms [17].

7.1. Hepatotoxicity

Hepatotoxicity is among the most extensively documented complications of AAS misuse. Although both oral and injectable preparations have been associated with liver injury, hepatotoxic effects appear particularly pronounced with 17α-alkylated oral steroids due to their resistance to first-pass hepatic metabolism [1,22].

Clinical manifestations range from asymptomatic elevations of liver enzymes to severe liver injury requiring hospitalization [1,22]. Reported abnormalities include elevations in alanine aminotransferase (ALT), aspartate aminotransferase (AST), alkaline phosphatase, and bilirubin concentrations [22].

Importantly, the severity of biochemical abnormalities does not always correlate with the extent of underlying hepatic injury. Some users may demonstrate substantial pathological changes despite relatively modest laboratory abnormalities, whereas others may remain asymptomatic for prolonged periods [1].

For adolescents, this issue may be particularly problematic because early symptoms are often nonspecific and may be attributed to intensive training, fatigue, or minor illness. Consequently, ongoing exposure may continue despite progressive hepatic injury [22].

7.2. Cholestatic Liver Injury

Among the most characteristic forms of AAS-induced hepatotoxicity is cholestatic liver injury. Numerous case reports and clinical series have documented severe cholestasis associated with anabolic steroid exposure, particularly following prolonged use of oral preparations [1,22].

Affected individuals may present with jaundice, pruritus, dark urine, pale stools, fatigue, and markedly elevated bilirubin concentrations [1]. Histopathological studies suggest that AAS may impair bile secretion and disrupt hepatocellular transport mechanisms, resulting in intrahepatic cholestasis [22].

Although many cases improve following discontinuation of steroid use, recovery may require several months, and severe cases occasionally necessitate intensive medical management [1]. Importantly, adolescents may not immediately associate symptoms such as fatigue or jaundice with AAS exposure, potentially delaying diagnosis and treatment.

Because steroid use frequently occurs outside medical supervision, hepatic complications may remain unrecognized until substantial injury has already occurred [22].

7.3. Hepatic Tumours and Long-Term Hepatic Risk

Long-term exposure to anabolic steroids has also been associated with hepatic adenomas and, more rarely, hepatocellular carcinoma [1,22]. Although these complications remain uncommon, they represent some of the most serious consequences of chronic AAS misuse.

The risk appears to increase with prolonged exposure, higher cumulative doses, and use of hepatotoxic oral compounds [22]. Hepatic adenomas may remain asymptomatic for extended periods but carry risks of haemorrhage, rupture, and malignant transformation [1].

While most available evidence originates from adult populations, these findings remain relevant to adolescent users. Individuals initiating AAS exposure during adolescence may accumulate substantially greater lifetime exposure than those beginning use later in adulthood. Consequently, even uncommon complications warrant consideration when evaluating long-term risk [17].

Importantly, current evidence does not support the assumption that younger age confers protection against steroid-induced liver injury. Rather, earlier initiation may increase cumulative exposure and potentially amplify long-term risk [1,22].

7.4. Renal Injury and Kidney Dysfunction

Growing evidence suggests that the kidneys may represent another target organ affected by AAS misuse. Reported renal complications include acute kidney injury, focal segmental glomerulosclerosis, proteinuria, nephrotic syndrome, and chronic kidney disease [11].

The mechanisms underlying AAS-associated renal injury are likely multifactorial. Proposed contributors include systemic hypertension, glomerular hyperfiltration associated with increased muscle mass, activation of profibrotic pathways, direct nephrotoxic effects, dehydration, and concurrent use of additional performance-enhancing substances [11].

Particularly concerning is the observation that renal injury may develop gradually and remain clinically silent during its early stages. Consequently, users may continue exposure despite progressive renal dysfunction, especially when laboratory monitoring is absent [11].

Assessment of renal function may be further complicated by common coexisting practices such as high-protein diets, creatine supplementation, stimulant use, and intensive resistance training. These factors may independently influence renal physiology and contribute to cumulative physiological stress on the kidneys [11].

Although severe renal outcomes remain relatively uncommon, current evidence supports viewing kidney injury as part of the broader multisystem toxicity associated with AAS exposure rather than as an isolated complication [11].

7.5. A Developmental Perspective on Organ Toxicity

From the perspective of developmental vulnerability, hepatic and renal complications provide an important reminder that AAS exposure affects far more than appearance, athletic performance, or reproductive function. The liver and kidneys are essential organs responsible for maintaining long-term metabolic and physiological homeostasis. Injury occurring during adolescence may therefore have implications extending across decades of future life [1,11,22].

Unlike acute adverse effects that become immediately apparent, hepatic and renal injury often develops gradually and may remain clinically silent until substantial dysfunction has occurred. This characteristic may be particularly relevant in adolescents, who frequently perceive themselves as healthy and relatively resistant to disease.

Current evidence therefore supports the view that hepatic and renal complications should be considered integral components of the overall health burden associated with adolescent AAS exposure. Although many questions remain regarding the long-term consequences of early exposure, available data consistently indicate that the potential for organ toxicity extends well beyond the endocrine and cardiovascular systems [1,11,22].

Biological toxicity alone does not fully explain why adolescents initiate and continue AAS use. Therefore, behavioural pathways from experimentation to persistent use should also be considered [14,15,21,26].

8. From Experimentation to Dependence: A Developmental Perspective

Understanding the biological consequences of anabolic-androgenic steroid (AAS) exposure is only part of the broader public health challenge. Equally important is understanding why some

adolescents progress from initial experimentation to persistent use despite increasing awareness of adverse health consequences. Current evidence suggests that this progression reflects interactions among psychological, social, and biological factors rather than a single isolated determinant [14,15,21,26].

8.1. Pathways to Initiation

The decision to use AAS often develops gradually rather than occurring as a single impulsive act. Many adolescents initially pursue conventional strategies to improve appearance or performance, including resistance training, dietary modification, and legal supplementation [14,16]. For some individuals, dissatisfaction with the pace of physical development and repeated exposure to physique-oriented online communities may gradually reduce perceived barriers to pharmacological enhancement [15,16].

Importantly, initiation is often driven by expectations of benefit rather than disregard for risk. Many users acknowledge potential adverse effects but perceive them as unlikely to occur personally or believe that complications can be prevented through information obtained from peers, online communities, or social media [15]. Initial experimentation does not necessarily lead to persistent use. However, rapid improvements in muscularity, strength, and appearance, together with positive social reinforcement, may encourage repeated cycles of AAS exposure and facilitate progression toward long-term use or dependence in susceptible individuals [17,18,21].

8.2. Poly-Substance Use and Broader Risk Behaviours

AAS use rarely occurs in complete isolation. Multiple studies have identified associations between steroid use and other forms of substance use, including alcohol, stimulants, cannabis, opioids, and additional performance-enhancing compounds [25].

This relationship is likely multifactorial. In some individuals, AAS use occurs within a broader pattern of health-risk behaviour, whereas others use additional substances to enhance performance, accelerate recovery, manage adverse effects, or alleviate withdrawal symptoms [17,25]. Schneider et al. demonstrated significant associations between adolescent AAS use and other substance-use behaviours, emphasizing that comprehensive assessment should consider coexisting substance use rather than AAS exposure in isolation [25].

9. Clinical and Public Health Implications

The growing prevalence of anabolic-androgenic steroid (AAS) exposure among adolescents presents challenges extending beyond sports medicine and endocrinology. Current evidence suggests that adolescent AAS use should be regarded as a multidisciplinary public health issue involving healthcare professionals, educators, parents, coaches, and policymakers [4,8,14,21,25]. Because the consequences of AAS exposure may affect multiple organ systems while simultaneously influencing psychological and social development, prevention and intervention efforts require a similarly multidimensional perspective.

Importantly, the developmental framework proposed throughout this review has practical implications for clinical decision-making. Adolescents should not be viewed simply as younger adult steroid users. Rather, they represent a population exposed during a period of ongoing biological and psychological maturation, potentially increasing both immediate and long-term vulnerability to harm [10,16].

9.1. Implications for Clinicians

Healthcare professionals are often among the first individuals capable of identifying early signs of AAS exposure. However, recognition may be challenging because adolescents frequently do not voluntarily disclose steroid use and may perceive healthcare providers as lacking expertise regarding performance-enhancing substances [14,17].

Clinicians should maintain awareness of potential indicators including rapid increases in muscle mass, severe acne, gynecomastia, testicular atrophy, unexplained hypertension, mood disturbances, aggressive behaviour, abnormal liver function tests, and unexpected dyslipidaemia in otherwise healthy adolescents [9,17,20,22].

Importantly, clinical encounters should avoid a purely punitive or judgmental approach. Adolescents may be reluctant to discuss AAS exposure if they anticipate criticism or stigmatization. A non-confrontational and evidence-informed discussion focused on health consequences and individual goals may improve disclosure and facilitate intervention [14].

Since many users obtain information from online communities rather than healthcare professionals, clinicians may also play an educational role by correcting misconceptions regarding the safety and reversibility of steroid-related complications [15,21].

9.2. Implications for Parents and Families

Parents often underestimate the likelihood of AAS use among adolescents because steroid misuse is frequently associated with elite athletes rather than otherwise healthy teenagers [4,25]. However, contemporary evidence suggests that appearance-related motivations may be equally important drivers of use [14,15,21].

Family environments may influence both vulnerability and protection. Open communication regarding body image, self-esteem, athletic performance, and social pressures may reduce susceptibility to harmful behaviours. Conversely, excessive emphasis on physical appearance, athletic success, or external validation may unintentionally reinforce risk factors associated with AAS exposure [16,21].

Parents should also be aware that early warning signs may be subtle. Behavioural changes, increasing preoccupation with muscularity, rigid dietary practices, excessive exercise, and disproportionate concern regarding physique may precede overt evidence of steroid use [21,26]. Recognition of these warning signs may facilitate earlier intervention before progression toward dependence or significant medical complications occurs.

9.3. Implications for Coaches, Trainers, and Educational Settings

Coaches and trainers occupy a unique position because they often interact with adolescents during periods of rapid physical development and athletic progression. Consequently, they may be among the first individuals to observe behavioural, physical, or performance-related changes potentially associated with AAS exposure [4,14].

Available evidence suggests that educational efforts may be more effective when they extend beyond traditional anti-doping messages. While emphasizing medical risks remains important, prevention initiatives may also benefit from addressing body image concerns, unrealistic expectations regarding physique development, and the influence of social media on perceptions of attractiveness and success [15,21].

Educational institutions may similarly provide opportunities for prevention through evidence-informed health education. Discussions regarding muscularity-oriented body image concerns, muscle dysmorphia, social media influences, and healthy approaches to physical fitness may address some of the underlying motivations associated with AAS use rather than focusing exclusively on medical complications [21,26].

Importantly, prevention strategies targeting only competitive athletes may overlook a substantial proportion of adolescent users whose primary motivation is appearance enhancement rather than sporting achievement [8,14].

9.4. Prevention Considerations

Current evidence suggests that prevention efforts may benefit from a developmental and multidisciplinary perspective. Approaches focused exclusively on medical complications may have limited effectiveness because many adolescents perceive long-term health risks as distant and abstract compared with immediate perceived benefits such as improved appearance, confidence, or social recognition [16,21].

Available evidence and theoretical models suggest that potentially beneficial approaches may include:

- promoting realistic expectations regarding physical development,
- addressing body dissatisfaction and muscularity-oriented concerns,
- improving media literacy,
- identifying adolescents with emerging muscle dysmorphia symptoms,
- supporting healthy training and nutrition practices,
- facilitating access to appropriate mental health resources [14,15,21,26].

Because body image concerns frequently precede AAS initiation, prevention programs may benefit from addressing underlying psychological vulnerabilities rather than focusing solely on substance use itself [21]. It should be acknowledged, however, that high-quality interventional studies specifically evaluating prevention strategies for adolescent AAS use remain limited. Consequently, many recommendations currently rely on extrapolation from broader adolescent health promotion and substance-use prevention frameworks.

9.5. Public Health Considerations

From a public health perspective, adolescent AAS exposure presents challenges extending beyond individual clinical encounters. The increasing accessibility of performance-enhancing substances through online marketplaces, social media platforms, and informal peer networks complicates traditional prevention efforts [15,16]. Furthermore, the growing normalization of pharmacologically enhanced physiques may contribute to changing social expectations

regarding male appearance and physical performance. This broader cultural environment may influence adolescents even when they are not directly involved in competitive sport [15,21]. Current evidence therefore supports viewing adolescent AAS exposure not only as a medical issue but also as a societal phenomenon influenced by technological, cultural, psychological, and developmental factors [15,16,21].

10. Limitations of Current Evidence

Although substantial evidence supports an association between anabolic-androgenic steroid (AAS) exposure and adverse health outcomes, several important limitations should be considered when interpreting the current literature. The most important limitation relates to the relative scarcity of adolescent-specific evidence. While the central focus of this review is adolescence as a unique period of developmental vulnerability, much of the available literature originates from adult AAS users, bodybuilders, athletes, or mixed-age cohorts [10,17,18]. Consequently, some conclusions presented in this review are based on a combination of adolescent-focused studies, adult clinical observations, developmental biology, and established physiological principles rather than direct longitudinal evidence in adolescent populations.

Second, observational and retrospective study designs predominate throughout the literature [17,23,24]. Such studies are valuable for identifying associations and generating hypotheses but generally cannot establish definitive causal relationships. Therefore, caution is warranted when interpreting the long-term consequences attributed to AAS exposure.

Third, accurate assessment of AAS exposure remains a substantial methodological challenge. Users frequently consume multiple compounds simultaneously, use unregulated products of uncertain composition, and may inaccurately report dosages, duration of exposure, or concurrent substance use [17]. These factors complicate comparisons between studies and contribute to heterogeneity across the literature.

Fourth, polysubstance use represents an important source of confounding. Many AAS users simultaneously report use of alcohol, stimulants, cannabis, opioids, growth hormone, insulin, or additional performance-enhancing substances [25]. Consequently, disentangling the independent effects of AAS from those of co-occurring exposures may be difficult.

Fifth, selection bias may influence the populations represented in clinical studies. Individuals experiencing severe complications may be more likely to seek medical attention and become

included in the literature, whereas asymptomatic users may remain underrepresented [17]. Conversely, users unwilling to disclose illicit substance use may be systematically excluded from research participation.

Sixth, substantial heterogeneity exists regarding the specific compounds studied. The term anabolic-androgenic steroids encompasses numerous substances that differ in pharmacokinetics, androgenic potency, aromatization potential, hepatotoxicity, and cardiovascular effects. Consequently, findings observed with one compound or exposure pattern may not necessarily be generalizable to all forms of AAS use [2,17].

Seventh, ethical considerations substantially limit prospective research involving adolescents. Randomized exposure studies are not feasible, and long-term observational investigations face important ethical, legal, and practical barriers [10]. As a result, many clinically relevant questions regarding the developmental consequences of adolescent AAS exposure remain unanswered.

Finally, contemporary patterns of AAS use may differ from those described in older studies. The growing influence of social media, online fitness communities, influencer culture, and muscularity-oriented body image concerns has altered the social context in which adolescents encounter and use these substances [15,21]. Consequently, historical studies may not fully capture the motivations, risk factors, and behavioural pathways characteristic of modern adolescent users.

Taken together, these limitations highlight the need for cautious interpretation of the available evidence. Nevertheless, the consistency of findings across endocrine, cardiovascular, neuropsychiatric, musculoskeletal, hepatic, and renal domains supports the conclusion that adolescence may represent a particularly vulnerable period for AAS exposure. While the precise magnitude of long-term risk remains incompletely defined, the available literature provides sufficient evidence to justify clinical concern and continued research in this area [9,10,17,20,22].

11. Conclusions

Anabolic-androgenic steroid exposure during adolescence represents a growing public health concern that extends beyond the traditional context of competitive sport. Current evidence suggests that adolescence may constitute a uniquely vulnerable developmental period during

which supraphysiological androgen exposure occurs in the setting of ongoing endocrine, reproductive, cardiovascular, musculoskeletal, neuropsychiatric, and psychosocial maturation.

Available data indicate that AAS exposure may suppress the hypothalamic-pituitary-gonadal axis, impair fertility, accelerate epiphyseal maturation, promote adverse cardiovascular remodeling, contribute to neuropsychiatric disturbances, increase susceptibility to connective tissue injury, and induce hepatic and renal toxicity [1,3,9,11,17,20,22]. While some adverse effects may improve following discontinuation, others may persist or result in potentially irreversible consequences.

Importantly, contemporary adolescent AAS use appears to be driven not only by athletic performance goals but also by muscularity-oriented body image concerns, social media influences, appearance-related pressures, and psychological vulnerabilities such as muscle dysmorphia [14,15,21,26]. Understanding these factors is essential for interpreting the growing prevalence of AAS exposure among adolescents and for developing effective prevention strategies. Despite important limitations within the current evidence base, findings across multiple biological and psychosocial domains consistently support the view that adolescents should not be regarded simply as younger adult steroid users. Rather, adolescence appears to represent a critical developmental window during which exposure to anabolic-androgenic steroids may interfere with processes that normally contribute to healthy physical and psychological maturation.

Future research should prioritize adolescent-specific longitudinal studies, improved exposure assessment, and integration of biological, psychological, and social determinants of AAS use. Such efforts may improve understanding of the long-term consequences of early exposure and support the development of more effective preventive and clinical interventions.

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Author Contributions

Conceptualization: K.P.

Methodology: K.P., W.P., J.K., K.S., M.S.

Data curation: E.B., A.T., A.B., M.Sz, F.T.

Writing: K.P., J.S.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI

During the preparation of this work, the authors used OpenAI ChatGPT for the purpose of basic data analysis and to identify linguistic patterns associated with specific logical fallacies. It is important to emphasize that the AI tool was used strictly as an assistive instrument under human supervision. Human experts in clinical medicine and formal logic determined the final interpretation of results, classification of errors, and conclusions, and take full responsibility for the substantive content of the publication.

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